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Final Report:
'Ice Shelves and Landfast Ice on the Antarctic Perimeter: Revised Scope of Work'

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Project Summary
Ice shelves respond quickly and profoundly to a warming climate. Within a decade after mean summertime temperature reaches ~0°C and persistent melt ponding is observed, a rapid retreat and disintegration begins. This link was documented for ice shelves in the Antarctic Peninsula region (the Larsen 'A', 'B', and Wilkins Ice shelves) in the results of a previous grant under ADRO–1. Modeling of shelf ice flow and the effects of meltwater indicated that melt ponding accelerates shelf breakup by increasing fracturing.

The ADRO-2 funding (topic of this report) supported further inquiry into the evolution of ice shelves under warming conditions, and the post-breakup effects on their feeder glaciers. Also, this grant considered fast ice and sea ice characteristics, to the extent that they provide information regarding shelf stability. A major component of this work was in the form of NSIDC image data support and in situ sea ice research on the *Aurora Australis* 'ARISE' cruise of September 9 2003 through October 28 2003.

Activities during Year 2 (Sept 2002 – Aug 2003) and No-cost Extension Period
Antarctic Ice Shelves and Larsen B Break-up Aftermath
Over the course of the past two years, the monitoring of ice shelf areas was expanded to include most of the major shelves of the Antarctic coastline and several persistent fast ice areas. This coverage is in the form of ~weekly clear-sky visible/NIR and thermal IR geo-located images of shelf front areas. The image gallery is available at the nsidc.org/agdc website (AGDC is the Antarctic Glaciological Data Center, supported by NSF-OPP Antarctic Glaciology)

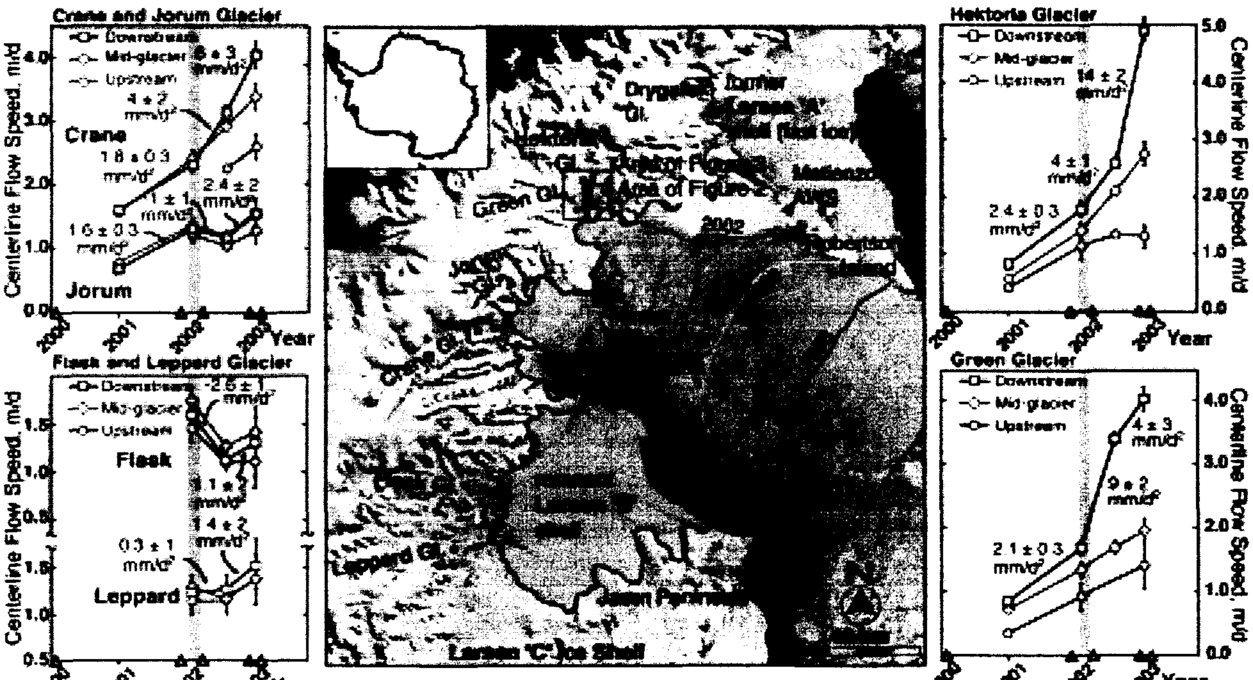
Continued evaluations of the Larsen B and C shelf fronts, post-2002-breakup, show little further climate-related change there. The past two austral summers (2002-03 and 2003-04), though warm, were not as extreme as the 2001-02 season. The remaining portion of the Larsen B shelf, filling most of Scar Inlet (the far southwestern portion of the original shelf, about 2500 km2 remaining) has shown some expanded rifting, and scattered melt ponding near the grounding line, but not the extensive pond coverage seen prior to the break-up of its northern sections. A medium-sized berg, A-52 (25x12 km), detached from the shelf in early 2003.

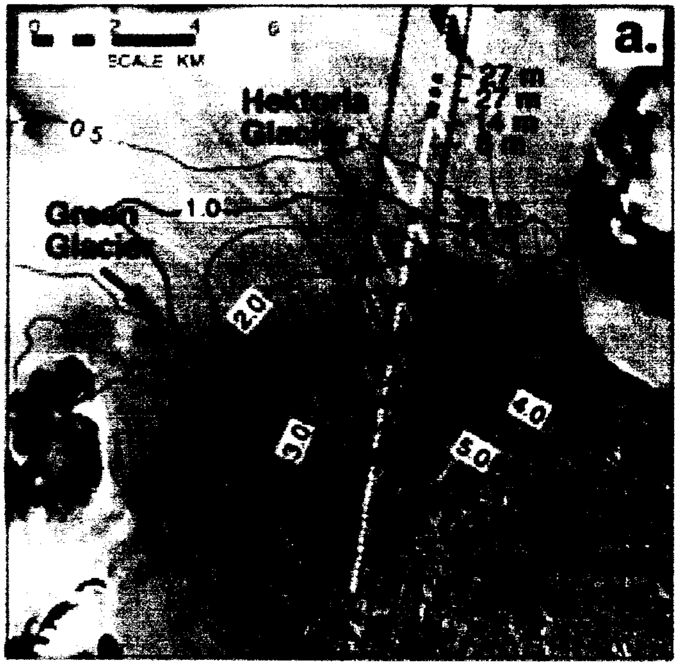
Effects of Larsen B Break-up on Feeder Glaciers

During 2003 and early 2004 (in the no-cost extension period) we used remaining funds from the grant to purchase a series of Landsat 7 images covering the glaciers that flowed toward the former Larsen B and its remaining areas to the south. Using the IMCORR software, we mapped ice flow over four periods, spanning the time before, during, and after break-up. The velocity data revealed a significant acceleration of all glaciers flowing into the vacated parts of the Larsen B embayment. Importantly, two patterns of acceleration were observed: a uniform acceleration of the lower glacier trunks, which we attribute to meltwater percolation through the glacier during the summer of 2001-02; and a very intense acceleration and longitudinal stretching of the lowermost glacier areas immediately following the loss of the shelf (within a few months). This second acceleration we attribute to a combination of loss of backstress from the shelf, and a steepening of the lower glacier surface as rapid, chaotic fracturing progressed up-glacier from the grounding line. Acceleration of the Hektoria/Green/Evans Glaciers increased their speed by a factor of 5 within the first year after the loss of the shelf. Glaciers flowing into the remaining shelf in the Scar Inlet showed no significant acceleration.

Further confirmation of rapid ice dynamics changes in the Hektoria Glaciers and other Larsen B glacier systems came from ICESat (Ice, Cloud, and land Elevation Satellite) measurements. Using both 8-day and 33-day repeat cycle data from the early Laser 1 and Laser 2 data acquisitions, elevations profiles revealed multi-meter lowering of the surface over the period March – September 2003, and September 2003 – February 2004. For the Hektoria Glacier, some areas in mid-glacier showed elevation decreases of 35meters and more over the six-month period.

These results were published in a paper in *Geophysical Research Letters*. A very similar result derived from InSAR measurements was published in the same GRL issue by Rignot et al.

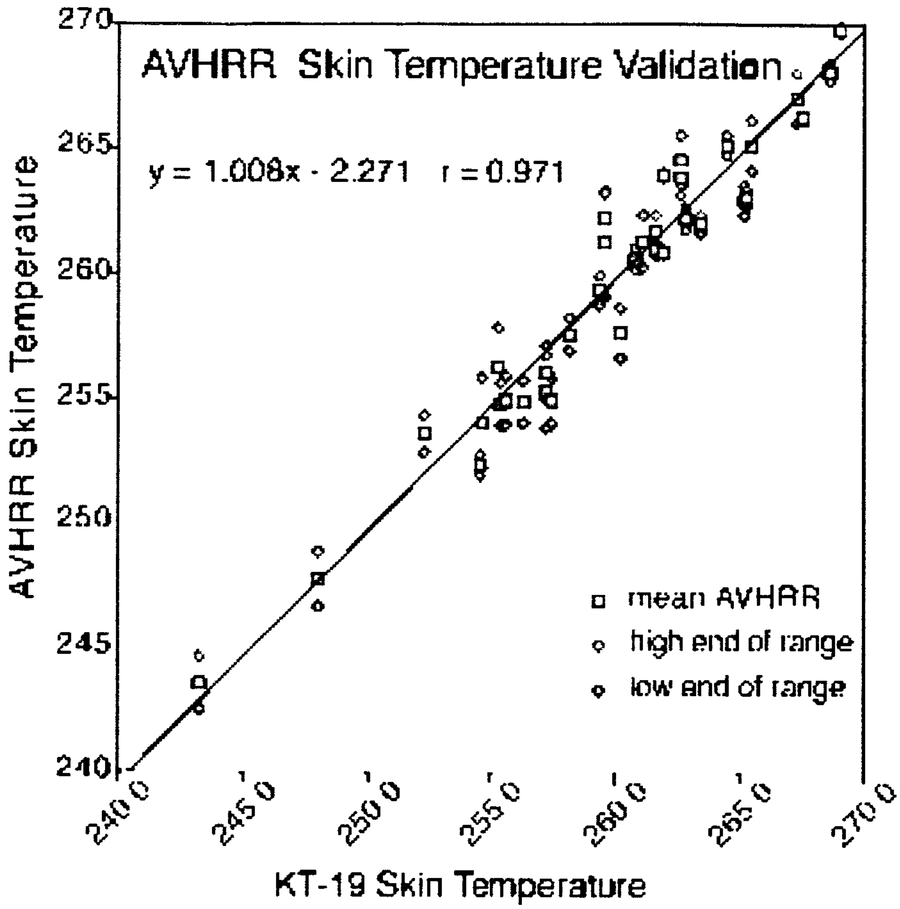




Sea Ice and Fast Ice Studies

A long-planned sea ice research cruise by the Australian Antarctic Division, with the objective of conducting a suite of calibration and validation studies on East Antarctic sea ice and fast ice, was conducted in September-October of 2003 (after two year's delay). The sea ice study is titled "ARISE: Antarctic Remote Ice Sensing Experiment". ADRO-2 funds provided by this grant supported *in situ* validation of AVHRR Polar Pathfinder temperature and albedo data by T. Haran and T. Scambos aboard the *Aurora Australis*. In addition, with funds from the NSIDC DAAC contract, T. Haran supported numerous other cal-val studies aboard ship by facilitating the transfer of Terra/Aqua sensor data to the ship in near-real-time for experiment planning and initial evaluation of field results.

The main result was a validation of the AVHRR Polar Pathfinder 1-km Ice Surface Temperature data set. Attached is a plot summarizing the validation. In situ measurements of skin temperature were made with a KT-19 thermal radiometer attached to the ship's rail. The field work led to a better appreciation of the potential differences between surface skin temperature and near-surface air temperature under clear-sky conditions. The strength (up to 12C in a 10m vertical interval) and rapidity (~30 minutes) with which a near-surface inversion can form over snow-covered surfaces in the polar regions under spring conditions (clouds and day-night cycle) was informative in evaluating future planned work investigating surface air and skin temperatures in West Antarctica.



Sea ice skin temperature validation for Polar Pathfinder 1-km AVHRR Ice Surface Temperature algorithm versus KT-19 in situ temperature measurement. Small regions of pixels from a few kilometer region around the ship were selected from ship-downloaded AVHRR-12, -15, and -16 images over the period September 25 through October 17. The regions were selected from ship-adjacent regions deemed to be free of sub-pixel leads. The processed, gridded ice surface (skin) temperature values were compared with skin temperature measurements from a rail-mounted KT-19 Thermal Radiometer. The radiometer values were averaged from 1-sec data for the periods near satellite overflight. A more detailed review of the measurements is given below.

KT-19 Setup on *Aurora Australis* ship's rail. Black 'Pelican' case contains battery system, data logger, and controlling laptop computer.

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APPENDIX:
Notes on AVHRR Thermal calibration during the Aurora Australis 2003 V1 cruise

The AVHRR Polar Pathfinder Ice Surface Temperature product was validated during the sea ice portion of the Aurora Australis 2003 V1 cruise. This was accomplished by comparing clear-sky satellite-derived skin temperatures with thermal radiometer measurements of the ice surface. Two radiometers were used; a rail-mounted device imaging a point adjacent to the ship; and a similar device mounted to a nadir viewport on a helicopter.

Rail-mounted system
The thermal radiometer used for the rail was a Heitronics KT-19.82, measuring the spectral range 8 to 14 microns. The device was mounted to the port side rail and pointed at the ice (or water) surface adjacent to the ship at a surface viewing angle of between 60 and 15 degrees below the horizon, with 30 degrees as the nominal value. Several tests of sensitivity to viewing angle showed variations of only a few tenths K, within the local variability due to ridges or sastrugi on the ice. The 30 degree viewing angle was intended to place the viewing area (roughly 0.5 meters across given the rail height, 15 meters , the field of view of the instrument) well to one side of the ship, to minimize the effect of ship-splash and fractures while underway. The radiometer was set in a foam-insulated box, and a self-regulating resistance heating system was installed to keep the instrument temperature at 280 +/- 3 K. A data rate of 1/sec was used. The device recorded temperature in kelvins, assuming an emissivity for all surfaces of 1.0. Sensitivity of the device (rms of a constant-temperature surface at 1 sec integration) was reported by the manufacturer as being 0.1K. The accuracy of the device was checked before and after most runs by viewing an ice-water bath. With emmisivity set to 1, under clear skies, this test consistently reported brightness temperature s of 272.2 – 272.6 (see below for later correction for emmisivity). Data were acquired for continuous multi-hour periods, spanning several overflights of the NOAA-12, NOAA-15, and NOAA-16 satellites during both day and night. Approximately 20 observing sessions were acquired over the period September 25 through October 21, 2003.

After acquisition, data were averaged to 1 minute intervals and compared with several additional parameters acquired during the cruise: GPS position, GPS speed, air temperature (@21 meters above the sea surface), solar radiation (a further indicator of cloudiness), wind, and data from another radiometer aboard, MAERI (Marine A E Radiometric Interferometer). In addition to minute-averaged mean KT-19 sensed temperature, the minimum, maximum, and standard deviation for the 60-second interval was recorded. MAERI data reported a skin temperature of the surface given an emissivity of 0.9635 (equal to seawater), averaged for 12 minutes.

Helicopter-mounted system
A similar unit, the Heitronics KT-19.85, was mounted to a nadir-viewing rack on a helicopter and flown on three days (September 29, October 8, and October 20, 2003) for several hours in the vicinity of the ship. This unit records emissions over the range 9 to 11 microns. The data were acquired every 2 sec, and the sensitivity (resolution) for the instrument at this rate is 0.1 K. Altitude of the helicopter was ~1500 meters. View area at this height is approximately 20 meters across. The helicopter unit was not temperature controlled, and internal temperatures varied from 275 to 295 K.

Satellite Images

Satellite data images from the AVHRR sensor on the NOAA-12, NOAA-15, and NOAA-16 satellites were downlinked as they flew overhead by the Terrascan system onboard the *Aurora Australis*. The satellite data were processed using the Polar Pahtfinder algorithms for both albedo and ice surface temperature. The data were gridded to a 1.25km grid in the Polar Pathfinder projection (Lambert Equal Area Polar Azimuthal). No cloud masking was applied; clear or cloudy sky conditions were determined by meteorological notes from aboard the ship, and examination of the albedo and thermal images.

Selection of validation points for the rail-mounted system

There were several factors considered in the selection of satellite-derived pixel values of skin temperature and mean KT-19 and MAERI data for comparison. These are a result of the spatial variability of the surface (sea ice and leads), the variation of temperature over time, and the movement of the ship through thick or thin ice. The ship was often on a boundary in temperature represented by a mixed-surface pixel in the gridded images. For this reason, a group of nearby pixels, covering areas that were interpreted to be homogenous at the 1.25km scale, were used for comparison with the rail-mounted KT-19 temperatures. The KT-19 measurements used for comparison were selected from times close to (+/- 30 minutes) the acquisition times that represented periods when the port side of the ship saw a uniform surface type for several minutes. For example, if ice floes were used for validation, pixels values were selected from floes within 25 km of the ship that showed uniform surface temperature. These were compared with the coldest, lowest-variability measurements from the KT-19 record near the time of satellite acquisition. For leads and polynyas, (usually covered with thin grey to grey-white nilas), a similar approach was used, taking uniform but warmer temperatures from both the image data and KT-19 record. Open water contamination was eliminated by selecting 60-second-mean points for which the maximum 1-sec temperature was less than 269 K.